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MODELLING OF ENERGY CONSUMPTION OF THE BATTERY ELECTRIC VEHICLE

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Abstract– Battery electric vehicles (BEVs) are gaining large market share. Accurate computation of the BEV's energy consumption is important to avoid running out of energy while driving. Therefore, it is important to develop a model which estimates the energy consumption of the BEV. This article describes a model that evaluates a BEV's energy consumption. The aim of this paper is modeling of BEV using MATLAB/Simulink software based on a real BMW i3 BEV 2014 data. The model consists of vehicle dynamics, single-speed transmission gearbox, electric machines and battery blocks. The detailed analysis on each block is performed and the governing equations for each block is derived taking into account both traction and regeneration modes. Moreover, constraints in terms of limitation in power for each block is considered. Finally, the results of the model are compared with the experimental data which obtained from Argonne national laboratory database in EPA Urban Dynamometer Driving Schedule (EPA UDDS) driving cycle.

Key words– BEV, EM, MATLAB, simulation, electric battery, UDDS

I Introduction

One of the main cause of environmental degradation around the world is global warming. CO2 and other gases exhausted by systems are main causes of global warming [1]. Therefore, the main goal of car manufactures all over the world is to develop zero-emission vehicles. On the other hand, measures are being taken to regulate the usage of natural resources. In this context, electrified vehicles are seen as the suitable solution [2]. One of the main advantage of BEV is the regenerative braking feature. However, still the market share of BEVs is not very fast. The main reasons for that are some limitations on charging stations, batteries cost and their life. The assessment of BEV's energy consumption has become an important task. The literature devoted to estimation of energy consumption of the electrified vehicle. Miri et al. used the MATLAB / Simulink based simulation modeling and estimation a BEV. The BEV energy consumption was modeled using longitudinal dynamics [2]. Synák et al. has used a dynamometric stand to determine the energy consumption of the BEV, experimentally. Dynamometer generates the mechanical energy transmitted through the car wheels to the traction motor and records the results using sensors connected to different parts [3]. Experimenting using this stand will also incur additional costs. The same dynamometric roller has also used in the work done by Konzept at al. The purpose of their work was to predict energy consumption of BEV in different driving cycles. In the end, the results were compared with a real driving speed profile and energy consumption recorded by an onboard computer of the vehicle [4]. The article does not take into account the influence of weather conditions and battery degradation. Thus, it can be concluded that vehicle modeling is the highest priority in the analysis of energy consumption. In an article presented by Suvak and Ersan, BEV was simulated in the MATLAB/Simulink program. Their article provided an analysis of the EM torque and power changes during the driving cycle. In addition, the power and torques generated by the wheels during the movement of the car was analyzed [5]. Simple yet efficient model for estimation of energy consumption of the BEV is missing. This article focuses on the analysis of energy consumption of the BEVs. The work describes a backward model to estimate energy consumption of BEV on different driving cycles. The model is validated using publicly available data from ANL [6].

II Vehicle modelling

In this section, full model of the BEV has been described. This analysis performed in the MATLAB / Simulink software and EPA UDDS drive cycle selected as the cycle of action which has shown in Figure 3. Simulated results are also compared with the experimental results in the section of RESULT. A detailed description of the measurement process has also given. In addition, the formulas used to calculate the vehicle's electric motor and battery parameters are given. The full model of the BEV has shown in Figure 1. This model allows to determine the state of charge (SOC) of the battery and energy consumption of BEV.

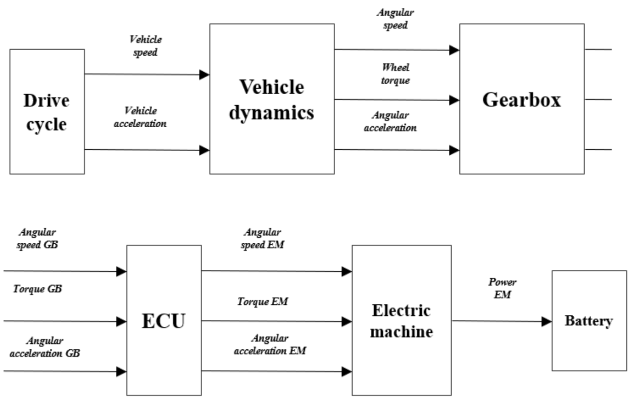

Fig. 1: Data flow for Backward model of BEV [7,8]

1 *VEHICLE SPECIFICATION*

BMW i3 BEV 2014 was selected for further analysis as the main technical specifications of the vehicle is publicly available and the most complete. The technical specifications of a vehicle are given in Table 1.

2 *VEHICLE MODEL*

Since this article focuses on evaluating the energy consumption of BEV, the following power analyzes are important for the implementation of this model:

- Analysis of the power from the battery to the wheels for the moving the vehicle
- Analysis of the power as a result of the regenerative braking of the vehicle
- Auxiliary power required to turn the additional equipment in the vehicle (air conditioning, etc.) and its analysis.

The data flow along each block is depicted in the Figure 1 are described sequentially.

3 *DRIVE CYCLE*

Drive cycle - is a time history of the vehicle speed. The drive cycle is used for vehicle testing and simulation as a standard form. Specifically, it is used to predict the performance of a vehicle's dynamics, emissions and comfort.

VEHICLE BODY	
Curb weight, (kg)	1443.3
Aerodynamic drag coefficient	0.3
Frontal area, (m^2)	2.38
POWERTRAIN	
Motor operating range, (rpm)	0-11 400
Maximum power kW / @ rpm	125 / @ 4777
Maximum torque Nm / @ rpm	250 / @ 0-4475
TRANSMISSION	
Type	Single-speed automatic transmission
Final gear ratio	8.2:1
Front/rear tyres radius, (m)	0.3290 (175/70 R19)
BATTERY	
Chemistry	Lithium-ion
Battery configuration	8 Modules (96 Cells Connected in Series)
Nominal cell voltage, (V)	3.7
Nominal cell capacity, (Ah)	60
Nominal battery pack voltage, (V)	355.2
Nominal battery pack capacity, (Ah)	60
Nominal battery pack energy, (kWh)	22

TABLE 1: BMW I3 BEV 2014 SPECIFICATIONS [2,6,9]

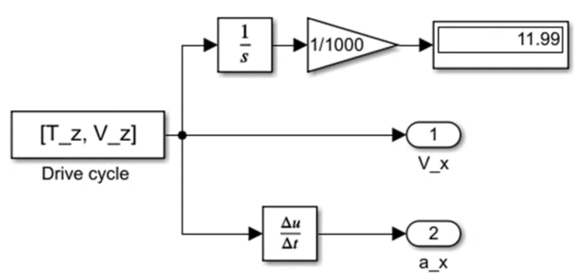

Fig. 2: Driving cycle model

The plot of the change in speed shown in Figure 3 and these values loaded into the block diagram in Figure 2. This block can also be used to represent the time dependence of a vehicle's acceleration (Eq.1.). Both experimental and theoretical data can be loaded into the driving cycle.

$$a_x = \frac{dV}{dt} \quad (1)$$

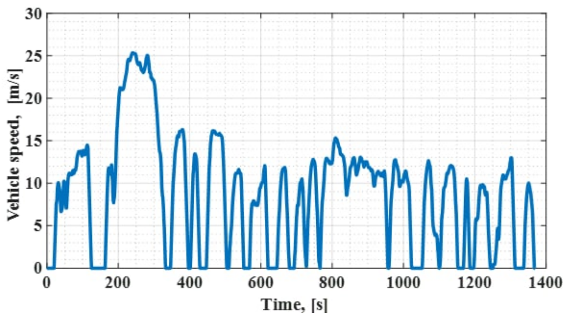

Fig. 3: Vehicle speed on EPA UDDS driving cycle

4 VEHICLE DYNAMICS

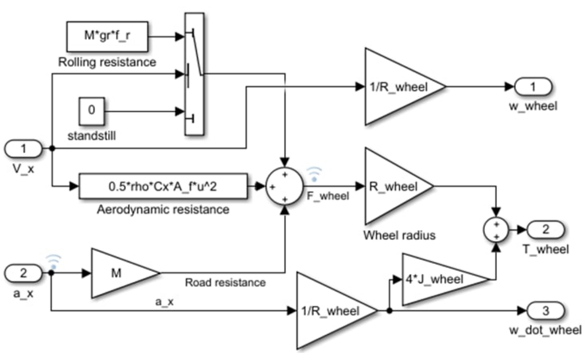

Fig. 4: Vehicle dynamics block

Vehicle dynamics - block studies the factors (angular velocity, forces, torque, etc.) that affect the movement of the vehicle and it is made up of forces that resist movement. Vehicle dynamics block is shown in Figure 4. The forces play a key role for driving the vehicle. This means that while the forces help the vehicle to move, they also resist the movement. These forces are transmitted from the electric motor to the wheels by means of a propulsion device to move the vehicle. The motion of a vehicle consists of the following forces that affect it: rolling resistance, aerodynamic drag force and the force generated by linear acceleration. The vehicle has to overcome resistance forces to move. Total force (F_t) determined by sum of the rolling resistance force (F_r), aerodynamic resistance force (F_a) and linear acceleration resistance force (F_m).

$$F_t = F_r + F_a + F_m \quad (2)$$

$$F_r = f_r \cdot M \cdot g \quad (3)$$

$$F_a = \frac{1}{2} \cdot \rho \cdot C_x \cdot A_f \cdot V^2 \quad (4)$$

$$F_m = M \cdot a_x \quad (5)$$

The output results from this block are shown in figure 4. They are angular speed (ω_w), angular acceleration ($\dot{\omega}_w$) and torque (T_w) in the wheels. Delivered power (P_w) to the wheel can determined by using Eq.9.

$$\omega_w = \frac{V_x}{R} \quad (6)$$

$$\dot{\omega}_w = \frac{a_x}{R} \quad (7)$$

$$T_w = F_t \cdot R + \dot{\omega}_w \cdot 4 \cdot J_w \quad (8)$$

$$P_w = F_t \cdot V_x \quad (9)$$

The output from this block to the GEARBOX block are the wheel torque Knowing (T_w) which depends also moment of inertia of the wheel (J_w) (Eq.8), wheel angular speed (ω_w) and acceleration ($\dot{\omega}_w$)

5 GEARBOX

In the Gearbox the angular speed and the torque generated from the vehicle's engine/motor are increased or decreased by a certain amount equal to transmission ratio (Fig.5.). In previous section, it was mentioned that the considered vehicle has a single – speed transmission. Hence, the value of the angular speed and the angular acceleration are changed while passing through the gearbox. These parameters are multiplied by the final gear ratio (U_f). U_f and efficiency of a gearbox (η_w) do not change due to the reason of single – speed transmission is used. One of the main functions of the transmission system is increasing of the torque between the electric motor and the wheel. The efficiency of the gearbox in the traction and braking mode can be inverted. For finding the torque and the efficiency of the gearbox, in the traction and braking modes approach proposed in [7] have been used.

The resulting equations are input parameters for the electric motor. It is necessary to determine the direction of power flow and this block is divided into two sub-blocks which are traction and braking modes. Depending on the movement of the vehicle, traction or braking mode is activated. The determined parameters are realized by the following equations 10 and 11.

$$\omega_{em} = \omega_w \cdot U_f \quad (10)$$

$$\dot{\omega}_{em} = \dot{\omega}_w \cdot U_f \quad (11)$$

Power mode block contains of following structure [7]:

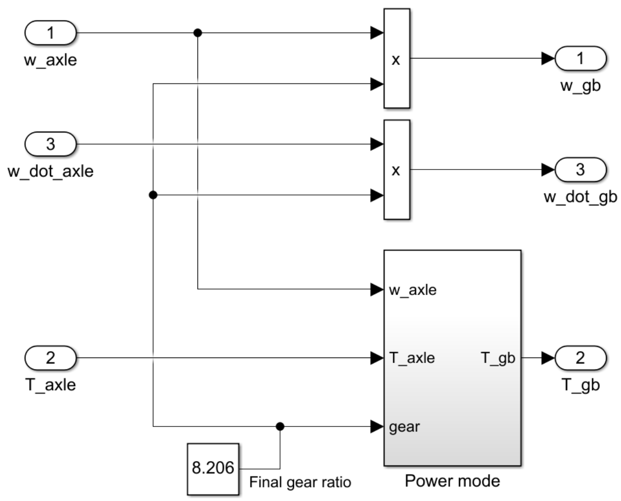

Fig. 5: GEARBOX block

$$T_{em} = \begin{cases} \frac{T_w}{\eta_{gb} \cdot U_f} & \text{– Traction mode} \\ \frac{\eta_{gb} \cdot T_w}{U_f} & \text{– Braking mode} \end{cases} \tag{12}$$

Where,

ω_{em} - angular velocity of electric machine [rad/s]

$\dot{\omega}_{em}$- angular acceleration of electric machine [rad/s^2]

η_{gb} - efficiency of a gearbox [-]

The transmission model is determined based on the following equation:

$$T_{em} = F_{tr} \cdot R \cdot U_f \cdot \eta_{gb} \tag{13}$$

Where,

F_{tr} – Traction force [N]

6 ELECTRIC MACHINE

Electric machine – is a machine which can convert electrical energy to mechanical energy when it works as a motor. In electric machine block, electric power can be determined from the electric motor torque and angular speed. The electric machine acts as a generator during the regenerative braking mode.

In backward model, Electric machine block demands an electric power from the battery packs. In general, the electric power from the battery is delivered to the electric motor. The movement of a vehicle is ensured as a result of the transmission through the gearbox to the wheels. The angular velocity and the torque can determine by using the Eq.10 and Eq.12. By using these parameters the electrical power (P_{em}) is determined. The auxiliary power (P_{aux}) is used by auxiliary components (air conditioner and etc.) of the BEV. It should be noted that the value of P_{aux} varies depending on the climate.

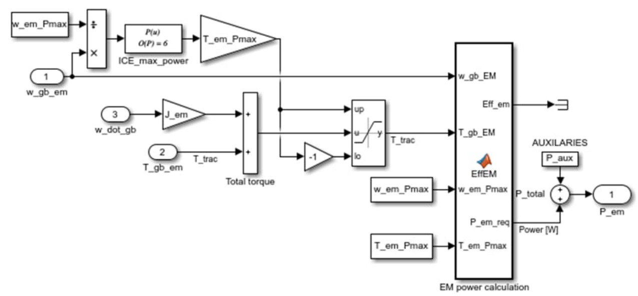

Fig. 6: Electric Machine block

For example, on a hot ambient temperature, more power is required as a result of using the air conditioner. So, the total electric power is determined by using the Eq.14. Model of the electric machine aims in calculating power demand from battery pack for given mechanical power, i.e., torque and speed of the electric machine at its output shaft. Scheme of this block is shown in Figure 6.

$$P_{em} = \omega_{em} \cdot T_{em} + P_{aux} \tag{14}$$

In this case, the maximum characteristic of the operation of electric machine is used in determining the minimum and maximum torque [8].The limits of T_{em} are following:

$$T_{max_{em}} < T_{em} < T_{min_{em}} \tag{15}$$

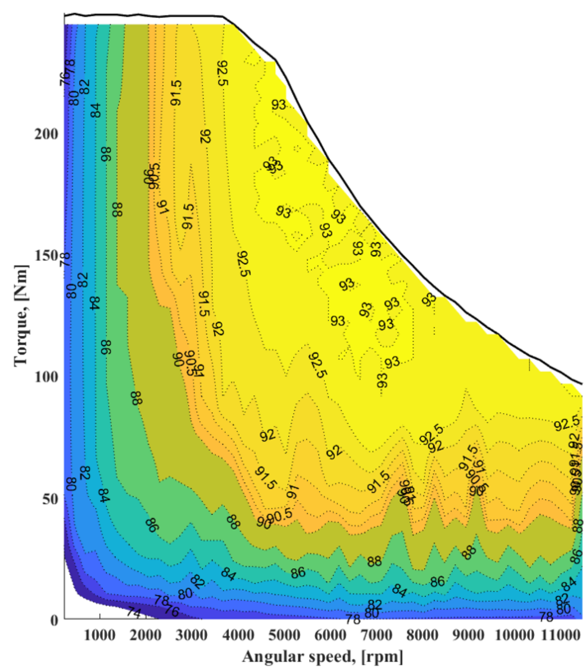

Fig. 7: BEV motor efficiency [2]

The efficiency of the electric motor (η_{em}) is formed as a function of the angular velocity (ω_{em}) and torque ($T_{tot_{em}}$) defines as follows:

$$\eta_{em} = f(\omega_{em}, T_{em}) \tag{16}$$

$$T_{tot_{em}} = T_{em} + J_{em} \cdot \dot{\omega}_{em} \tag{17}$$

where,
J_{em} - moment of inertia of electric machine $[kg \cdot m^2]$

7 BATTERY

Battery – is the main source of the vehicle to power the electric motor. Battery block analyses the required electric current and voltage during the driving cycle. In addition, it can study variation of state of charge (SOC).

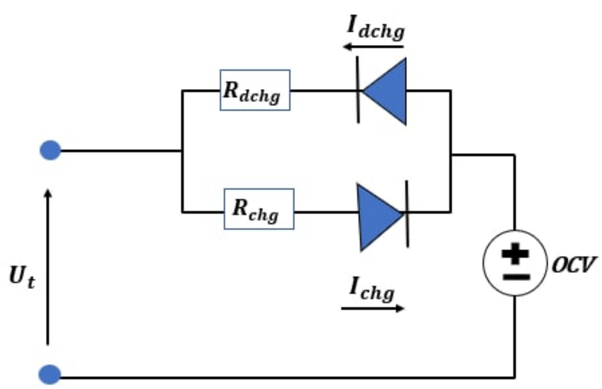

Fig. 8: Battery electrical circuit model (Thevenin model)

Thevenin model it can be used to model Open circuit voltage (OCV), charging (R_{chg}) and discharging (R_{dchg}) resistance as functions of SOC:

$$OCV = f(SOC), \;\; R_{chg} = f(SOC), \;\; and \;\; R_{dchg} = f(SOC) \tag{18}$$

The SOC of the battery is if charge and discharge modes are calculated in the following equation:

$$SOC = \begin{cases} SOC_i - \frac{\int_o^t I_{dchg} dt}{Q_{nom}} & - \quad \text{Traction mode} \\ SOC_i + \frac{\int_o^t I_{chg} dt}{Q_{nom}} & - \quad \text{Braking mode} \end{cases} \tag{19}$$

Where,
SOC_i – initial value of state of charge [-]
Q_{nom} – nominal value of the battery capacity [Ah]
I_{dchg} – value of discharge current [A]
I_{chg} – value of charge current [A]

By knowing the value of charging (R_{chg}) and discharging (R_{dchg}) resistances and OCV it should be evaluated the I_{dchg} and I_{chg} by solving the following quadratic equations:

$$I_{dchg} = SOC_i - \frac{OCV - \sqrt{OCV^2 - 4 \cdot R_{dchg} \cdot P_{bat}}}{2R_{dchg}} \tag{20}$$

$$I_{chg} = SOC_i - \frac{-OCV + \sqrt{OCV^2 - 4 \cdot R_{chg} \cdot P_{bat}}}{2R_{chg}} \tag{21}$$

There are restrictions on the battery performance in terms of maximum charging and discharging currents values. It is therefore important to ensure that the current discharged from the batteries does not overcome the limiting conditions.

$$I_{chg} < I_{chg_{max}} \;\; and \;\; I_{dchg} < I_{dchg_{max}} \tag{22}$$

Where,
$I_{chg_{max}}$ - maximum value of charge current [A]
$I_{dchg_{max}}$ - maximum value of discharge current [A]

From the Thevenin model battery power (P_{bat}) also analysed for the given components. Power balance equation is applied to equivalent circuit[11].

$$P_{bat} = \begin{cases} I_{dchg} \cdot OCV - I_{dchg}^2 \cdot R_{dchg} & - \text{Traction mode} \\ I_{chg} \cdot OCV + I_{chg}^2 \cdot R_{chg} & - \text{Braking mode} \end{cases} \tag{23}$$

The OCV relative to SOC has illustrated in Figure 9a. It can be seen from the graph that the voltage has nearly linear dependence from SOC in the region of interest (0.1 – 0.9). The internal resistances of the battery in charging and discharging phases are shown in Figure 9b and Figure 9c respectively.

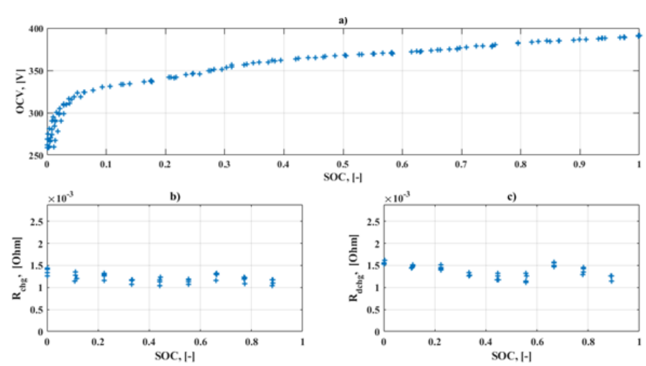

Fig. 9: OCV, R_{dchg} and R_{chg} analysis by SOC

The main purposes are changing values of SOC, current and voltage by time during driving cycle and these can be estimate by the battery model in MATLAB/Simulink. Battery

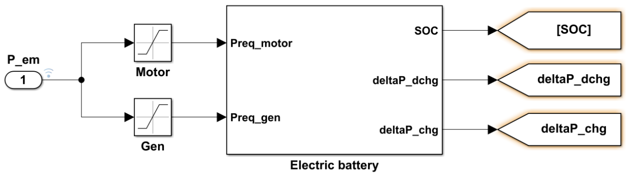

Fig. 10: Battery model

model is illustrated in Figure 10. It can be seen the electric battery can take electric power from the electric machine block and works in charging/discharging mode.

Electric battery part separates charging and braking mode which is shown in Figure 11. Electric battery polynomials used to find OCV and finally get a SOC, these values are calculated by equation 18 and 19 respectively.

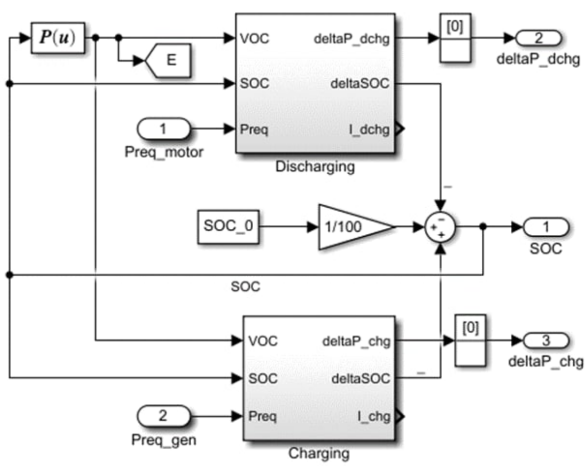

Fig. 11: Working principle of charging/discharging of the battery

III RESULTS

When the model is launched, several results can be obtained. Electrical energy is converted into the mechanical energy to generate mechanical torque and angular velocity on the wheels. Power loss from the battery to the wheels through the gearbox is in the range of 5 - 10 kW. Comparison results between the mechanical and electrical power is shown in Figure 12.

SOC of the battery has been simulated theoretically and illustrated in blue dotted line in Figure 13. This theoretical graph was compared with the result of real experimental data available from [6]. The difference between them is marginal. This may be due to the fact that complete data (i.e., rolling resistance coefficient, aerodynamic drag coefficient, auxiliary

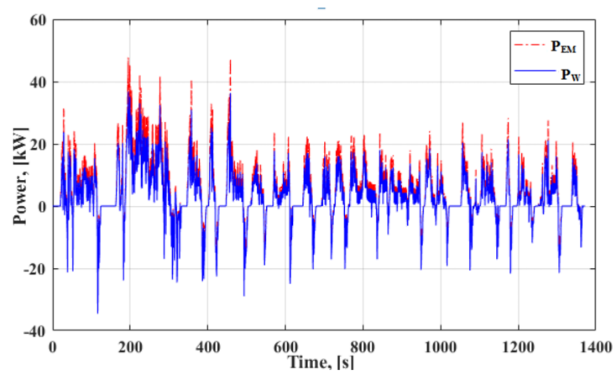

Fig. 12: Comparison of the electric and mechanical power time history over UDDS cycle

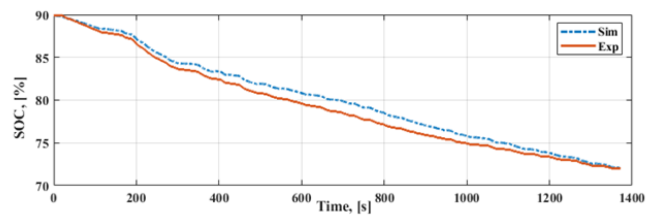

Fig. 13: SOC during the drive cycle

power) are different from these used in experiment.

IV CONCLUSION

The purpose model is a complete model of BEV and consists of several blocks. These blocks include: Driving cycle, vehicle dynamics, gearbox, electric machine and battery blocks. The drive cycle is represented by a data of the changing vehicle speed over time and the UDDS drive cycle was used during the testing of this model. The SOC of the battery was compared with the experimental results.

Mechanical power is slightly less than electric power, where the difference is around 5-10 kW. These losses occur mainly in the motor and gearbox block. The charge level of the car differs by a small amount compared to the experiment. The main reason for this is the lack of data on auxiliary power, rolling resistance, aerodynamic drag coefficients. The model results show good correlation with experiments. The future work will analyse the influence of the motor, battery characteristics on the energy consumption calculation results.

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